Towards a direct route to turbulence in an open rotating cavity

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The transition to turbulence is analyzed in an annular cavity made of two parallel co-rotating disks of finite radial extent, fed by a forced inflow at the hub. This configuration provides a simple model of technological devices such as turbo-machinery and it is also relevant to geophysical flows (Launder *et al.* 2010). In the limit of large rotation, centrifugal and Coriolis forces produce a secondary flow in the meridian plane composed of two thin boundary-layers along the disks separated by a non-viscous geostrophic core where the axial gradient of pressure nearly equilibrates the Coriolis force. The flow stability is primarily governed by the disk boundary-layers and the waves they support that can be locally analysed by reference to theoretical results from infinite disks. Early results of local linear stability analysis are the object of a general agreement (Launder *et al.* 2010) and have revealed that such boundary layer is subject to two generic types of instability referred as type I (crossflow) and type II (viscous).

New interest has been stimulated by the experimental and theoretical studies of Lingwood (1996, 1997) which showed that the onset of absolute instability in both the von Kármán and Ekman layers adjacent to a single disk occurred at a value of Reynolds number which closely corresponded to that obtained experimentally for laminar-turbulent transition. This major contribution to the turbulent breakdown process opened the possibility of a direct route towards turbulence through a global instability. But to this day, if further studies have confirmed these local linear stability results, no general agreement exists concerning their outcome in terms of global behaviour due to the competition between nonlinear and nonparallel effects. Numerical investigations of the linearized Navier Stokes equations by Davies & Carpenter (2003) showed that non-parallel effects can stabilize the flow whereas Pier (2003) assuming the existence of a non-linear global mode and computing the non-linear homogenous wave that should immediately follows the front, showed this primary nonlinear global mode should therefore be unstable toward a secondary instability with the possibility of a rapid transition to turbulence shortly behind the primary front. In such context, study of transition to turbulence must incorporate both nonlinear (destabilizing) and nonparallel effects (stabilizing).

The impulse response of the boundary layer in sectorial cavities of azimuthal extent $2\pi/68$ and $2\pi/4$ has been investigated by pseudo-spectral DNS. Numerical results establish the existence of a primary subcritical bifurcation to nonlinear global mode with angular phase velocity and radial envelop coherent with the so-called elephant mode theory (Pier & Huerre 2001). Numerical observations of an elephant mode agrees with Pier's conjecture (Pier 2003) on the existence of a nonlinear global mode due to the presence of an absolutely unstable region, even when the flow is linearly globally stable (Davies & Carpenter, 2003). Moreover, this self-sustained saturated wave is itself globally unstable. A second front appears in the lee of the primary where small-scale instability develops with characteristics indicating a Floquet mode of zero azimuthal wavenumber. This secondary instability leads to a much disorganized state, defining transition to turbulence. This transition, linked to the secondary instability of a global mode, confirms for the first time on a real flow the possibility of a direct transition to turbulence through an elephant cascade, a scenario up to now only observed on the Ginzburg-Landau model.

Further work investigates alternative routes, when the initial perturbation is very low or when the azimuthal wavenumber is limited to smaller values.

References

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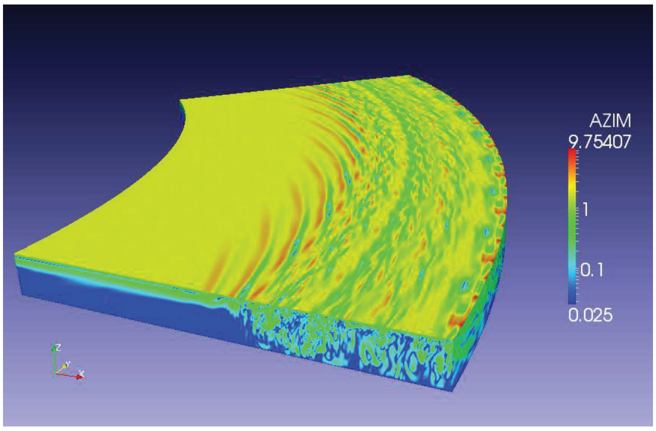

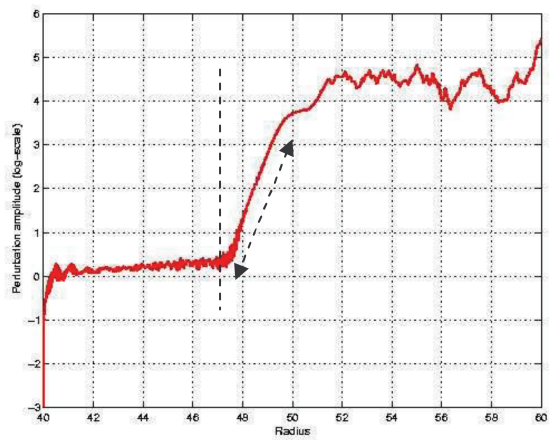

Flow pictures for Cw = 1995, Reh = 780 (Re_ 2 [330; 491], Ro 2 [−0.9;−0.45]). On the left, iso-lines of vorticity showing the saturated primary spiral front (m=68) followed by turbulence. On the right, profile of the linear-log amplitude of the perturbation-energy of m = 68 as a function of the radial coordinate. The radial position of the primary front is located at the transition from convective to absolute instability at r_c=43 and its slope matches the expected slope according to elephant-mode theory.